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Two-Neutron Sequential Decay of $^{24}$O

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Abstract
A two-neutron unbound excited state of $^{24}$O was populated through a $(d,d')$ reaction at 83.4 MeV/nucleon. A state at $E = 715 \pm 110$ (stat) $\pm 45$ (sys) keV with a width of $< 2$ MeV was observed above the two-neutron separation energy placing it at $7.65 \pm 0.2$ MeV with respect to the ground state. Three-body correlations for the decay of $^{24}$O $\to ^{22}$O + 2n show clear evidence of a sequential decay through an intermediate state in $^{23}$O. Neither a di-neutron nor phase-space model for the three-body breakup were able to describe these correlations.

Disciplines
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fragments were swept 43.3° from the beam axis by a 4-Tm superconducting sweeper magnet [27] into a series of position- and energy-sensitive charged particle detectors. Two cathode-readout drift chambers (CRDCs), separated by 1.55 m, were placed after the sweeper and measured the position of the charged fragments. Immediately following the CRDCs was an ion chamber which provided a measurement of energy loss, and a thin (5 mm) dE plastic scintillator which was used to trigger the system readout and measure the time-of-flight (TOF). Finally, an array of CsI(Na) crystals stopped the fragments and measured the remaining total energy. The position and momentum of the fragments at the target were reconstructed using an inverse transformation matrix [28], obtained from the program COSY INFINITY [29].

Element identification was accomplished via a ΔE vs TOF measurement, and isotope identification of 22O was accomplished through correlations between the time-of-flight, dispersive angle, and position of the fragments. Additional details on this technique can be found in Ref. [30]. The neutrons emitted in the decay of 24O traveled 8 m undisturbed by the magnetic field towards the Modular Neutron Array (MoNA) [31] and the Large-area multi-Institutional Scintillator Array (LISA). MoNA and LISA each consist of 144 200 × 10 × 10 cm3 bars of plastic scintillator with photomultiplier tubes on both ends which provide a measurement of the neutron time-of-flight and position. MoNA and LISA each contain nine vertical layers with 16 bars per layer. The combined array was configured into three blocks of detector bars. LISA was split into two tables, four and five layers thick, with the four-layer table placed at 0° in front of MoNA, while the remaining portion of LISA was placed off axis and centered at 22°. The resulting angular coverage was from 0° < θ < 10° in the laboratory frame for the detectors placed at 0°, and 15° < θ < 32° for the off-axis portion. Together MoNA, LISA, and the charged particle detectors provide a complete kinematic measurement of the neutrons and charged particles, from which the decay of 24O can be reconstructed.

The momentum vectors of the neutrons in coincidence with 22O were calculated from their locations in MoNA-LISA. Neutron interactions were separated from background γ rays by requiring a threshold of 5 MeV of equivalent electron energy (MeVee) on the total charge deposited. In addition, a time-of-flight gate on prompt neutrons was also applied.

Neutron interactions were separated from background γ rays by requiring an energy distribution parameter ϵassociated with a neutron. The invariant mass for an N-body system, MN-body, is the invariant mass of the N-body system, M22O, the mass of 22O, and mn the mass of a neutron. The invariant mass for an N-body system was calculated from the experimentally measured four-momenta of 22O and the first N − 1 time-ordered interactions in MoNA-LISA. In this analysis, we consider both the two- and three-body decay energies. The T and Y Jacobi coordinate systems were used to define energy and angular correlations in the three-body decay of 24O. These correlations can be described by an energy distribution parameter ϵ = E_s/E_T, and an angle cos(θ_k) = k_x · k_y/(k_xk_y) between the Jacobi momenta k_x and k_y [1].

In constructing the three-body system and its correlations, it is crucial to identify events which are true 2n events as opposed to a single neutron scattering twice. This is accomplished by selection on the relative distance D12 and relative velocity V12 between the first two interactions in MoNA-LISA. By requiring a large relative distance D12, events which scatter nearby are removed, and events with a clear spatial separation are selected. Since a neutron will lose energy when it scatters, an additional cut on V12 will also remove scattered neutrons. In this analysis, we require D12 > 50 cm, and V12 > 12 cm/ns which is the beam velocity. This technique has been used in several measurements of two-neutron unbound nuclei to discriminate against 1n scatter [11,13,23,32–37]. To further enhance the 2n signal, an additional threshold of 5 MeVee is applied to every hit recorded in MoNA-LISA.

A Monte Carlo simulation was used to model the decay of 24O and included the beam characteristics, the reaction mechanism, and subsequent decay. The efficiency, acceptance, and resolution of the charged particle detectors following the dipole sweeper magnet and MoNA-LISA were fully incorporated into the simulation, making the result directly comparable with experiment. The neutron interactions in MoNA-LISA were modeled with GEANT4 [38] and a modified version of MENATE [39] where the 12C(n, p)11B inelastic cross section was modified to better agree with an earlier measurement [40].

In principle, 22O can be populated by multiple paths in this experiment as illustrated in Fig. 1. The first is by neutron knockout to an unbound state in 23O; another is by inelastic excitation of the beam above the two-neutron separation energy. Hence, it is important to consider both the one- and two-neutron decay energy spectra. This is done by a simultaneous minimization of the log-likelihood ratio on three experimental histograms: (a) the 22O+1n decay energy, (b) 22O+2n decay energy, and (c) the 22O+2n decay energy with the causality cuts shown in Fig. 2. This method provides additional constraints over fitting each histogram individually.
In this formalism, a distribution for the relative energy of the two neutrons $E_r = \epsilon_1 - \epsilon_2$ is calculated as a function of the total decay energy $E$. The first neutron, with kinetic energy $\epsilon_1$, decays from an initial state with energy $E_1$ and width $\Gamma_1$, to an intermediate unbound state $E_2$, $\Gamma_2$, which proceeds to decay by emitting another neutron with kinetic energy $\epsilon_2$. Assuming a spin antisymmetric pair of neutrons, the total amplitude for the decay becomes

$$A_T(\epsilon_1, \epsilon_2) = \frac{1}{\sqrt{2}} \left( \frac{A_1(\epsilon_1)A_2(\epsilon_2)}{\epsilon_1 - [E_2 - \frac{1}{2}\Gamma_2(\epsilon_2)]} + \frac{A_2(\epsilon_2)A_1(\epsilon_1)}{\epsilon_2 - [E_2 - \frac{1}{2}\Gamma_2(\epsilon_1)]} \right),$$

where $A_1$ and $A_2$ are the single-particle decay amplitudes, and $\Gamma_i$ are proportional to the energy-dependent single-particle decay widths by a spectroscopic factor. The Fermi golden rule then gives the partial decay width as

$$\frac{d\Gamma(E)}{d\epsilon_1 d\epsilon_2} = 2\pi\delta(E - \epsilon_1 - \epsilon_2)|A_T(\epsilon_1, \epsilon_2)|^2,$$

and the cross section is approximated as an energy-dependent Breit-Wigner with the differential written in terms of the relative energy:

$$\frac{d\sigma}{dE_r} \propto \frac{1}{(E - E_1)^2 + \Gamma_T^2(E)/4} \frac{d\Gamma(E)}{dE_r},$$

where the total width $\Gamma_T(E)$ is obtained from

$$\Gamma_T = \int dE_r \frac{d\Gamma(E)}{dE_r}.$$

It should be noted that this formalism assumes that the two neutrons come from the same orbital and are coupled to a $J^n = 0^+$. The best fit for the decay of $^{23}$O and $^{24}$O is shown in Fig. 2. Using previously reported values for states in $^{23}$O \cite{23,41,42,44}, we obtain good agreement with the data. The two-neutron decay energy spectrum with the causality cuts is shown in Fig. 2(c). The best fit for the three-body decay gives an energy of $E = 715 \pm 110$ (stat) $\pm 45$ (sys) keV, and $\Gamma < 2$ MeV, which agrees with previous measurement \cite{23}. Only an upper limit can be put on the width, since the width is dominated by the experimental resolution. The best fit is shown using the single-particle decay width of $\Gamma_{\text{spw}} = 120$ keV. Using a value of $S_{2n} = 6.93 \pm 0.12$ MeV \cite{26} places the state at an excitation energy of $7.65 \pm 0.2$ MeV. No branching through the $3/2^+$ state in $^{23}$O was necessary to fully describe the data.

The two- and three-body decay energies, along with the causality cuts, are well described by the sequential decay, where each decay proceeds by emission of an $L = 2$ neutron. The data are largely dominated by the direct population of $^{23}$O; however, the one-neutron decay is unable to describe the three-body energy with causality cuts and the corresponding three-body correlations.

The relative energy and angle in the $T$ system is shown for three-body events with causality cuts in Fig. 3(a). In addition to the sequential decay [Fig. 3(b)], two other models were tested: the di-neutron decay [46] [Fig. 3(c)], and an (uncorrelated) phase-space decay [47] [Fig. 3(d)]. In the di-neutron decay the two neutrons are emitted as a pair.
FIG. 3. (Color online) Jacobi relative energy and angle spectra in the T system for the decay of $^{23}\text{O} \rightarrow ^{22}\text{O} + 2n$ with the causality cuts applied and the requirement that $E_{\text{decay}} < 4$ MeV. Shown for comparison are simulations of several three-body decay modes: a sequential decay (b), a di-neutron decay with $\alpha = -18.7$ fm (c), and a phase-space decay (d). The amplitudes are set by twice the integral of the three-body spectrum with causality cuts.

which subsequently breaks up, and so they have an angular correlation that peaks at $-1$ in the Y-system $\cos(\theta_k)$. In contrast to the sequential and di-neutron emission, the phase-space decay assumes no correlations between the neutrons and distributes their energy evenly.

It is evident that two-neutron decay does not proceed by di-neutron nor by uncorrelated emission and is much better described by the sequential decay, demonstrating that two-neutron decay passes through an intermediate state instead of directly populating $^{22}\text{O}$.

Figure 4 shows the best fit of the energy and angle correlation in the T and Y system for a sequential decay. It includes contributions from false 2n events shown in shaded gray. They are clearly distinct from the correlations for the sequential decay. Most notable is the $\cos(\theta_k)$ in the T system which exhibits strong peaks at 1 and $-1$ with a valley in between. Similarly, the relative energy spectrum in the Y system is peaked around 0 and 1. The ratio $E_s/E_T$ in the Y system is indicative of how the energy is shared between the neutrons, where a peak at 1/2 implies equal sharing. The data show unequal sharing, which indicates a sequential decay through a narrow state that is closer to the final state than it is to the initial state (or vice versa).

This is what we expect given that the three-body state in $^{23}\text{O}$ is at 715 keV, while the intermediate state in $^{23}\text{O}$ is narrow and low lying at 45 keV. In the two-proton decay of $^6\text{Be}$ [7], it was observed that the sequential decay was suppressed until the total decay energy was greater than twice the intermediate state plus its width. Here, this condition is certainly fulfilled. The depth of the valley in the $E_s/E_T$ spectrum is slightly softened by contamination from false 2n events. In the analysis of the two-proton decay of $^6\text{Be}$, the data could not be described by either of three simple models (di-proton, sequential, direct) and a more complex fully three-body dynamical calculation was used to describe the data. Although the present data show clear evidence for a sequential two-neutron decay in $^{24}\text{O}$, a similar three-body calculation would be valuable to fully understand the decay mechanism.

In summary, a state above the two-neutron separation energy in $^{24}\text{O}$ was populated by inelastic excitation on a deuterium target. The data are well described by a single resonance at $E = 715 \pm 110$ (stat) $\pm 45$ (sys) keV. Examination of the three-body Jacobi coordinates shows strong evidence for a sequential decay through a low-lying intermediate state in $^{23}\text{O}$ at 45 keV. The di-neutron or phase-space models are unable to reproduce these correlations. Unlike other systems that decay by emission of two neutrons and show evidence for di-neutron decay [11,13], the decay of $^{24}\text{O} \rightarrow ^{22}\text{O} + 2n$ has unambiguously been determined to be a sequential process.

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